Recent Experience in Random Vibration Moment Limiting

Michael B. Van Dyke

Jet Propulsion Laboratory / California Institute of Technology

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Spacecraft Mechanical Section/Dynamic Environments & Aerospace Nuclear Safety Engineering

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National Aeronautics and Space Administration

Overview

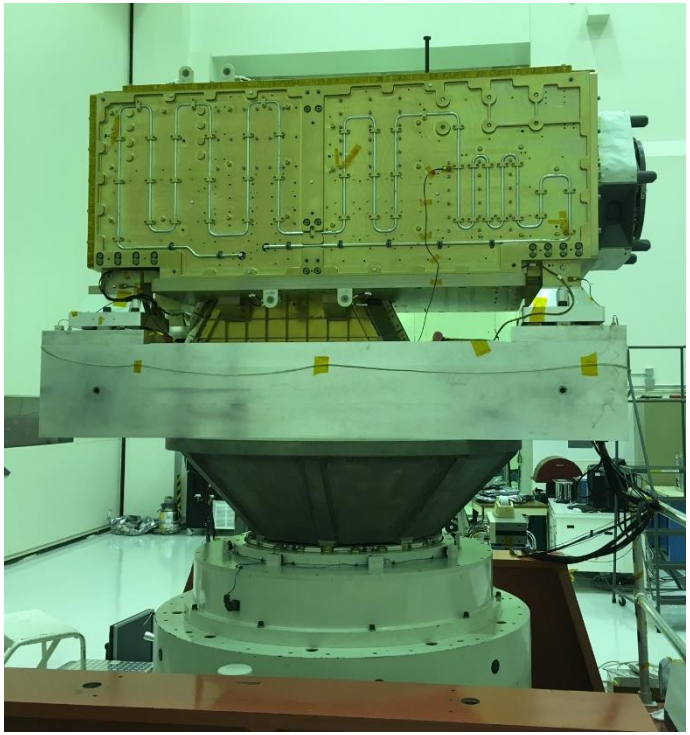
- Overturning moment during vertical axis vibe contributed by
  - Static lateral c.g. offset of test article and GSE
  - Dynamic reaction of test article at its base I/F
  - Cross-axis inertial response of GSE mass below test article I/F

- Inertial response of GSE mass observed to be a dominant contributor, particularly due to
  - Massive GSE
  - Test article dynamics reacting significant shear forces at I/F
  - Cross-axis response to resonance of GSE/head expander

- Moment limiting implemented to control contribution from both test article dynamics and GSE inertial response
  - To prevent exceeding overturning moment capability of shaker

Necessity for Overturning Moment Limiting

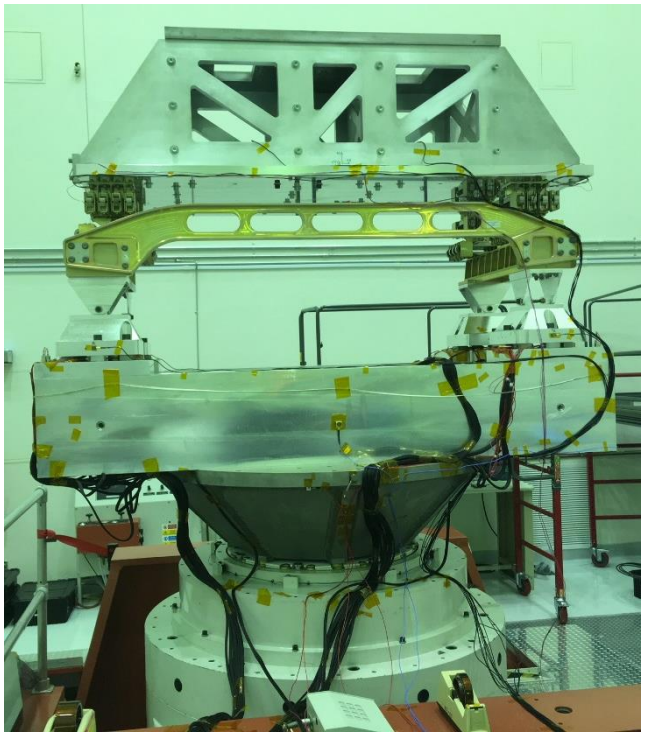
Ecostress Instrument



Test Articles
~1300-1500 lbs

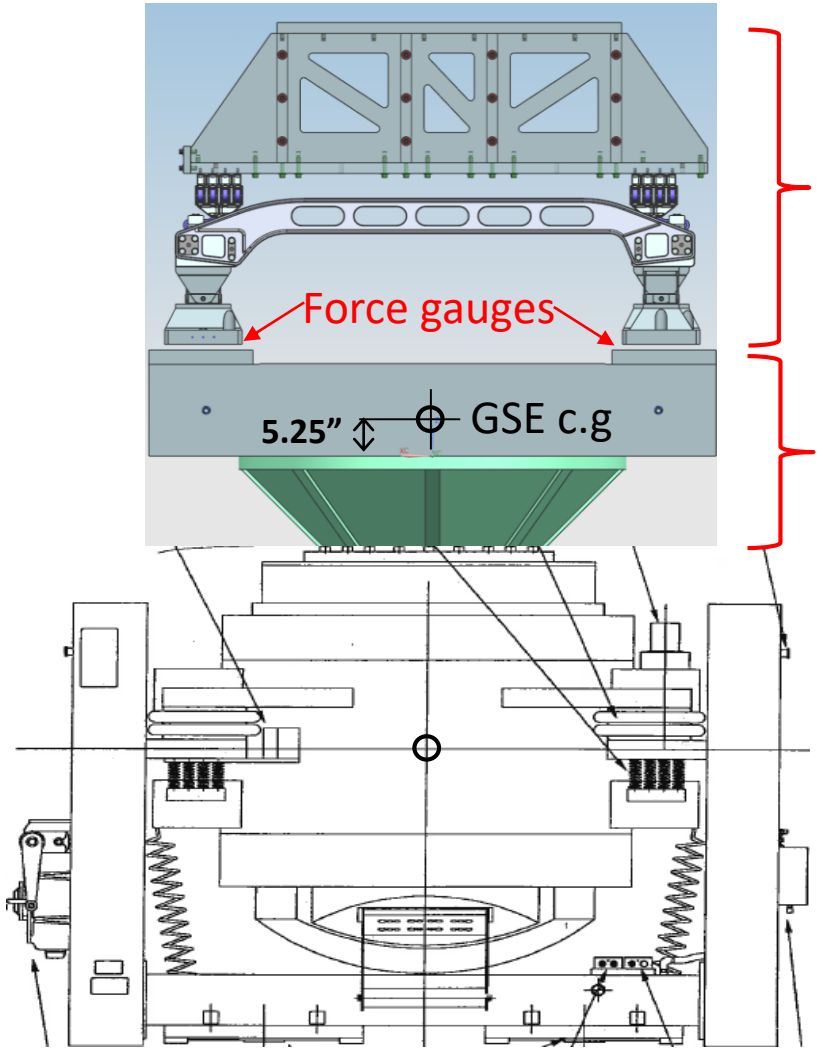
GSE:
Vibe Fixture 3317 lbs
Head Expander 526 lbs

LVIS Isolation System with OCO-3 Mass Sim



- Wide test article footprint relative to head expander drove massive fixture design to keep fixture modes above 250 Hz
- Dynamic overturning moment for Z-Axis random vibration test predicted to exceed rated capability of ETL V994 shaker (97k in-lbs) with current head expander
- Presentation will focus on LVIS/OCO-3 work as example

Measuring Overturning Moment (OTM)



Dynamic moment of test article

- OTM calculated from I/F reaction forces
  - Measured by force gauges

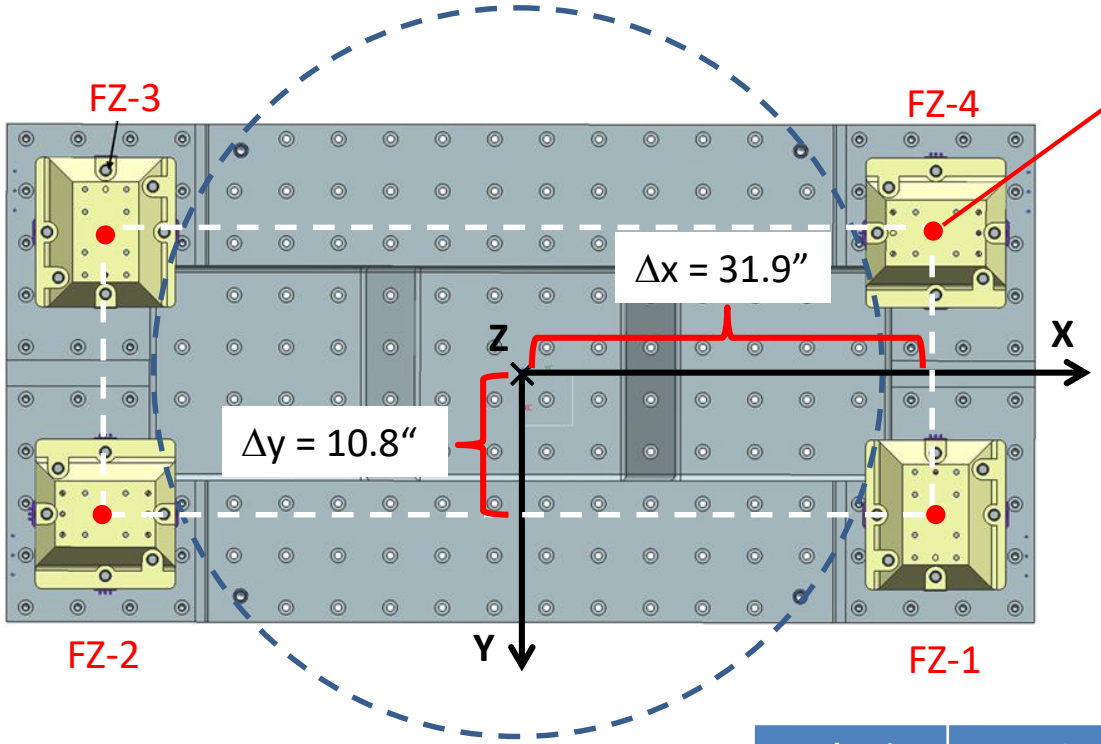
Inertial response moment of GSE

- OTM Calculated from lateral acceleration of GSE effective mass
  - Measured by GSE c.g. accel signals

Setting Up

For Test Article Dynamic OTM based on I/F Forces

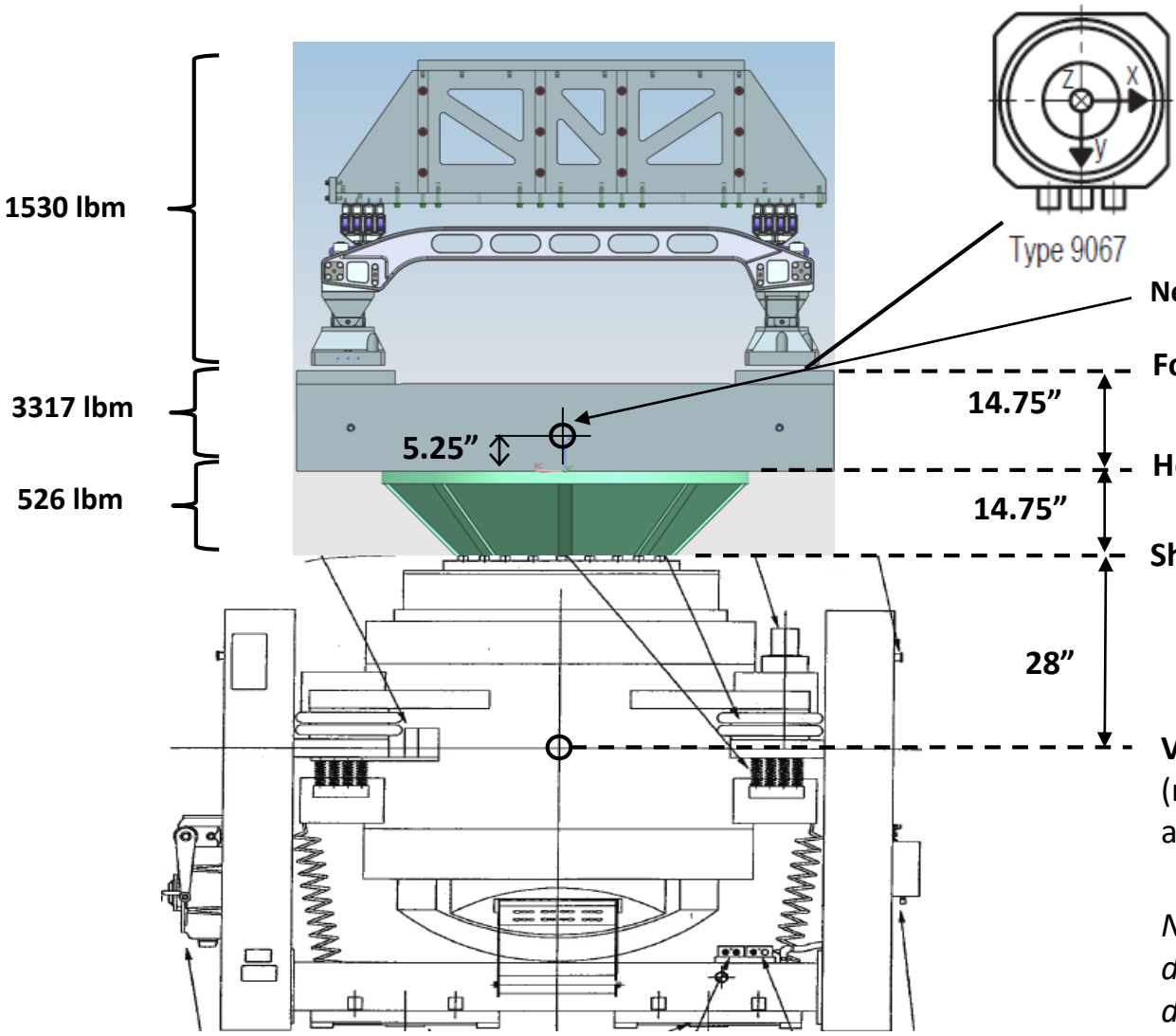
Load Point Moment Arm Values



Centroid of 6 force gauges (beneath foot plate)

Load Point	Force Gauges	Δx (in)	Δy (in)	Δz (in)
FZ-1	1-6	+ 31.9	+ 10.8	- 58.3
FZ-2	7-12	+ 31.9	- 10.8	- 58.3
FZ-3	13-18	- 31.9	- 10.8	- 58.3
FZ-4	19-24	- 31.9	+ 10.8	- 58.3

Vertical Dimensions re V994 Point of Rotation



Calculating Overturning Moment from Reaction Forces

- Overturning moment about origin (from multiple point forces):

$$M = \sum_{n=1}^{N} \Delta r_n \times F_n$$

$$\rightarrow M_x = \sum_{n=1}^{N} \left(\Delta y_n F_{zn} - \Delta z_n F_{yn} \right)$$

$$\rightarrow M_y = \sum_{n=1}^{N} \left(\Delta z_n F_{xn} - \Delta x_n F_{zn} \right)$$

- Simplification for constant Δz:

$$M_{x\_total} = \sum_{n=1}^{N} \left(\Delta y_n F_{zn} \right) + \Delta z \sum_{n=1}^{N} F_{yn} + dy(mg)$$

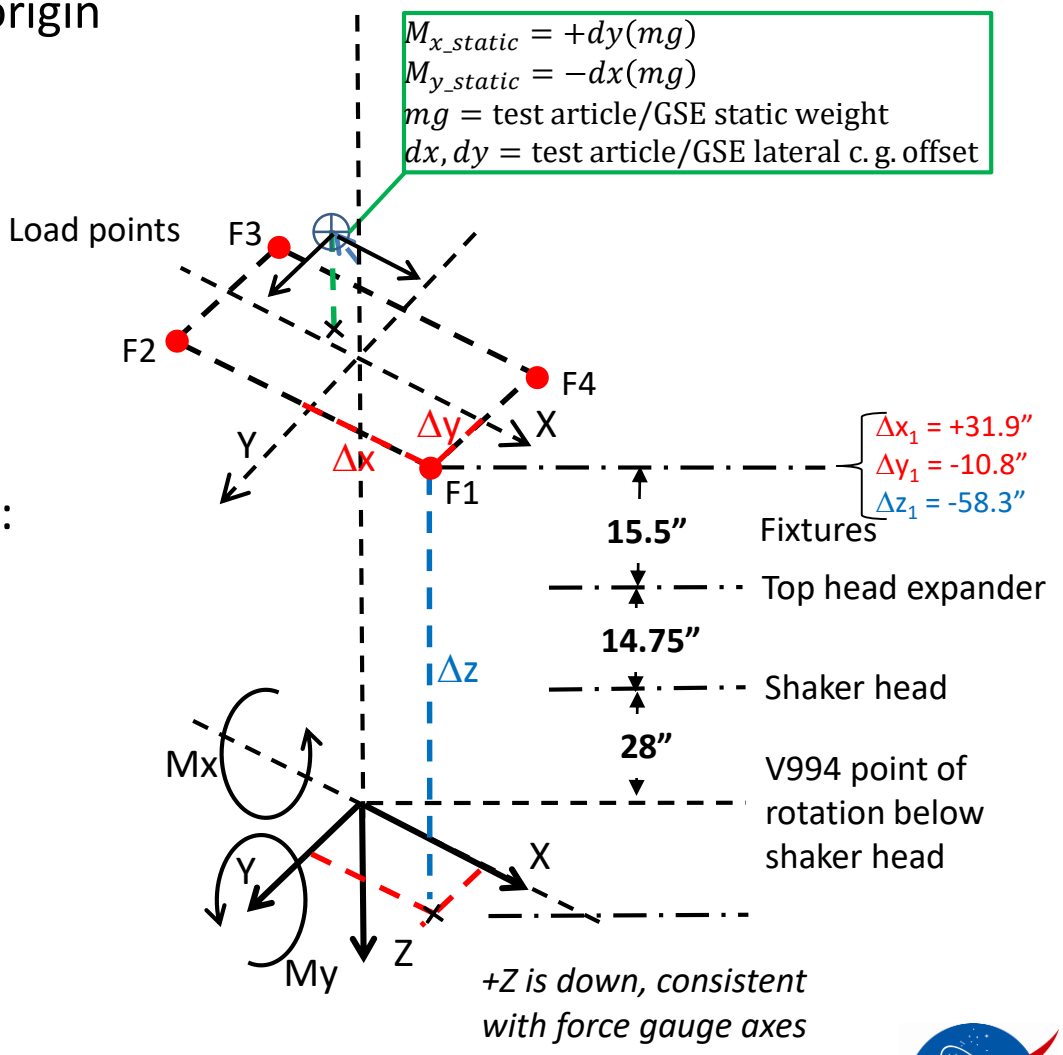
$$M_{y\_total} = \Delta z \sum_{n=1}^{N} F_{xn} - \sum_{n=1}^{N} \left(\Delta x_n F_{zn} \right) - dx(mg)$$

$$\left| M_{xy\_total} \right| = \sqrt{M_{x\_total}^2(t) + M_{y\_total}^2(t)}$$

Dynamic normal force component

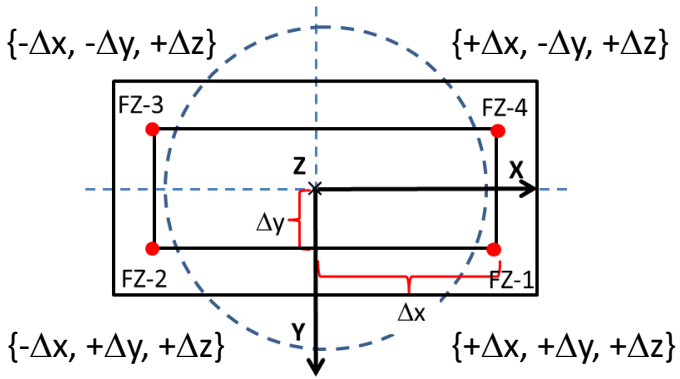
Dynamic shear force component

Static moment



Simplification for Symmetric Rectangular Geometry

- Load points symmetrical wrt to shaker central axis



$$M_x = \sum_{n=1}^{N}\left(\Delta y_n F_{zn}\right) - \Delta z \sum_{n=1}^{N} F_{yn}$$

Shear force component

$$= \Delta y F_{z1} + \Delta y F_{z2} - \Delta y F_{z3} - \Delta y F_{z4} - \Delta z \sum_{n=1}^{N} F_{yn}$$

Normal force component

$$= \Delta y\left(F_{z1} + F_{z2} - F_{z3} - F_{z4}\right) - \Delta z \sum_{n=1}^{N} F_{yn}$$

$$M_y = \Delta z \sum_{n=1}^{N} F_{xn} - \sum_{n=1}^{N}\left(\Delta x_n F_{zn}\right)$$

$$= \Delta z \sum_{n=1}^{N} -\Delta x F_{z1} + \Delta x F_{z2} + \Delta x F_{z3} - \Delta x F_{z4}$$

$$= \Delta z \sum_{n=1}^{N} F_{xn} + \Delta x\left(-F_{z1} + F_{z2} + F_{z3} - F_{z4}\right)$$

Amplifiers Employed

1 Multi-Function Amplifier

Kistler 5017A Multi-channel Charge Amp
8-channel charge amp for force gauges

- 4-channel summing functions

$$\Sigma Fz = \tfrac{1}{4}(Fz_1 + Fz_2 + Fz_3 + Fz_4)$$
$$Mx = \tfrac{1}{4}(Fz_1 + Fz_2 - Fz_3 - Fz_4)$$
$$My = \tfrac{1}{4}(-Fz_1 + Fz_2 + Fz_3 - Fz_4)$$

Single Function Amplifiers

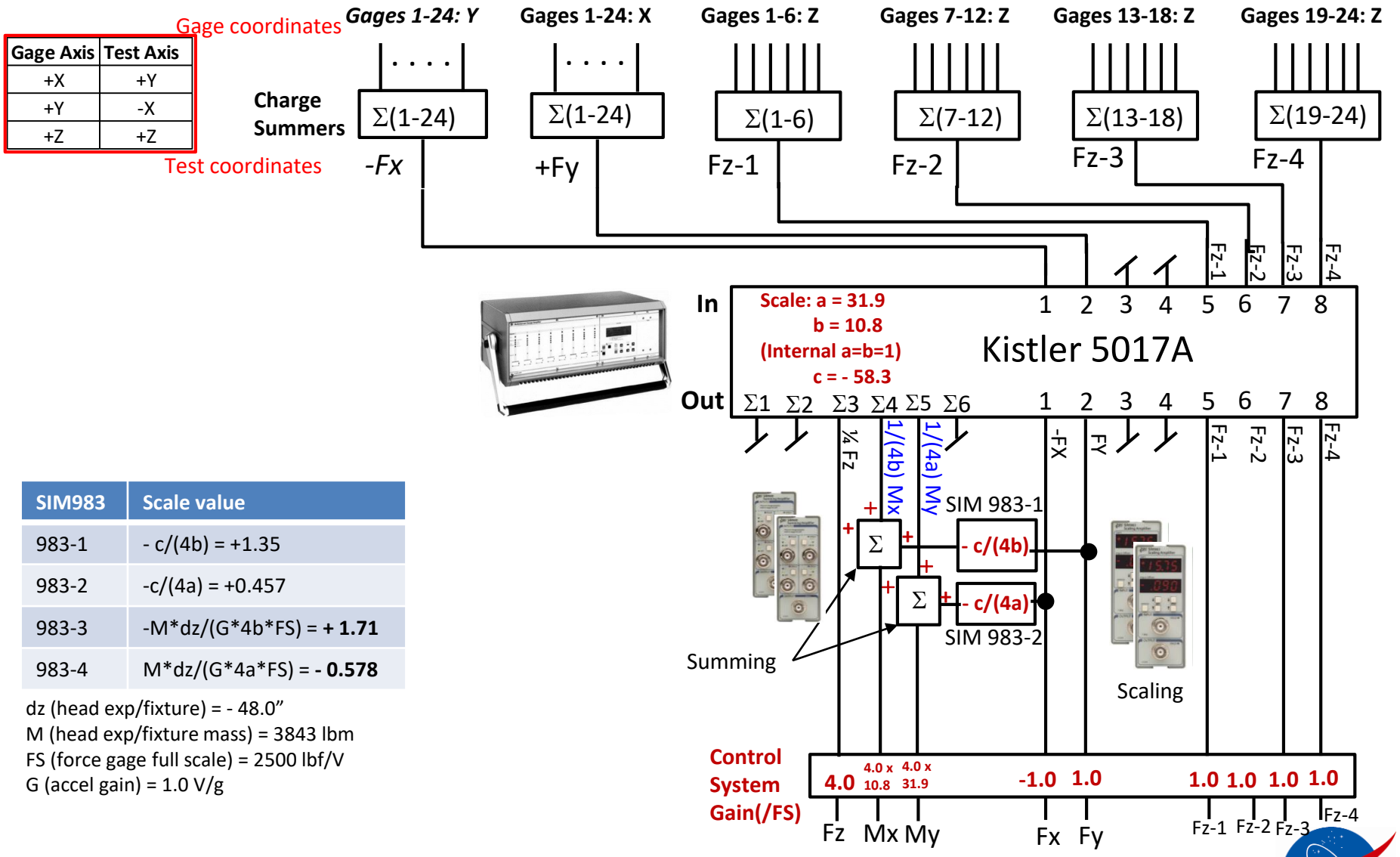
2- SRS SIM980 Summing Amplifiers
- $y = \pm x_1 \pm x_2 \pm x_3 \pm x_4$

4 SRS SIM983 Scaling Amplifiers
- Single channel
- Gain: 0.01 to 19.99

SRS SIM900 Main Frame
- Powers SIM980's and SIM983's

Dynamic Moment Limiting Network

Gage Axis	Test Axis
+X	+Y
+Y	-X
+Z	+Z



SIM983	Scale value
983-1	- c/(4b) = +1.35
983-2	-c/(4a) = +0.457
983-3	-M*dz/(G*4b*FS) = **+ 1.71**
983-4	M*dz/(G*4a*FS) = **- 0.578**

dz (head exp/fixture) = - 48.0”
M (head exp/fixture mass) = 3843 lbm
FS (force gage full scale) = 2500 lbf/V
G (accel gain) = 1.0 V/g

Setting Up

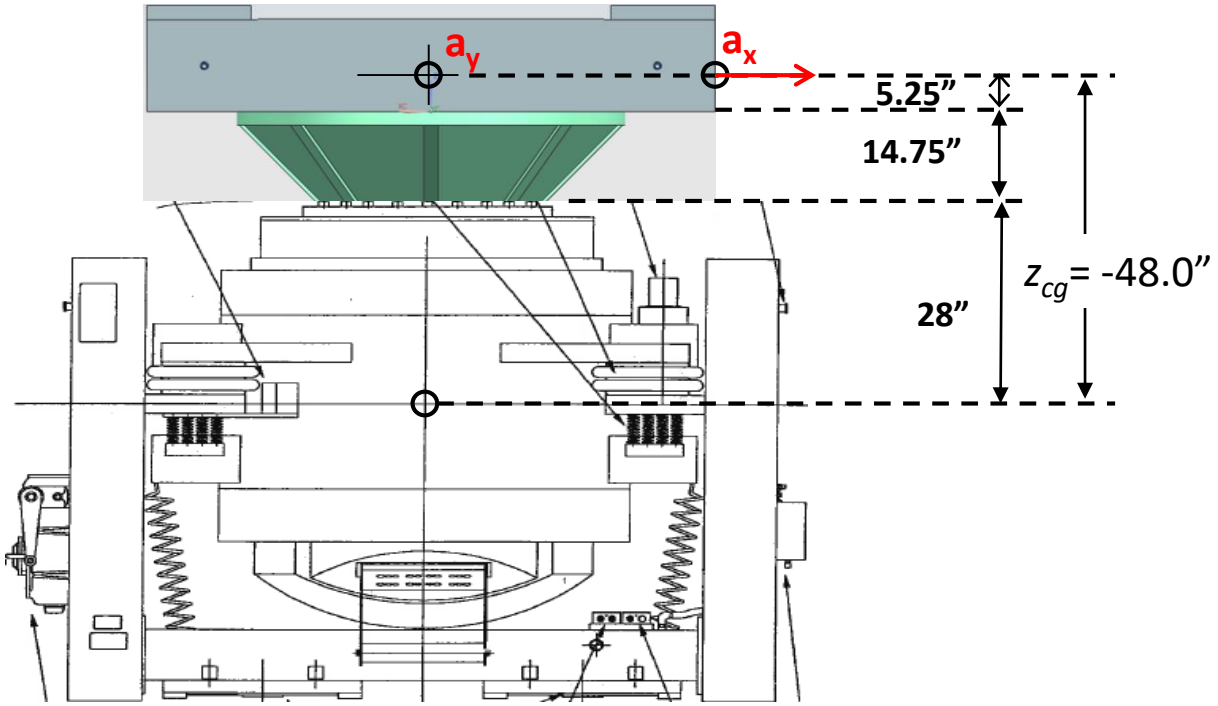
For GSE Inertial OTM based on c.g. acceleration

Inertial Overturning Moment Limiting Implementation

- Necessary also to include moment contribution of the masses below the force gauges (and above the shaker head) of the GSE (head expander and fixture)

$$M_x = -\ddot{x}_y m_{eff} z_{cg}$$
$$M_y = \ddot{x}_x m_{eff} z_{cg}$$

m_{eff} = effective mass of fixture/head expander first lateral mode = 3843 lbm



Dynamic and Inertial OT Moment Limiting Network

Gage Axis	Test Axis
+X	+Y
+Y	-X
+Z	+Z

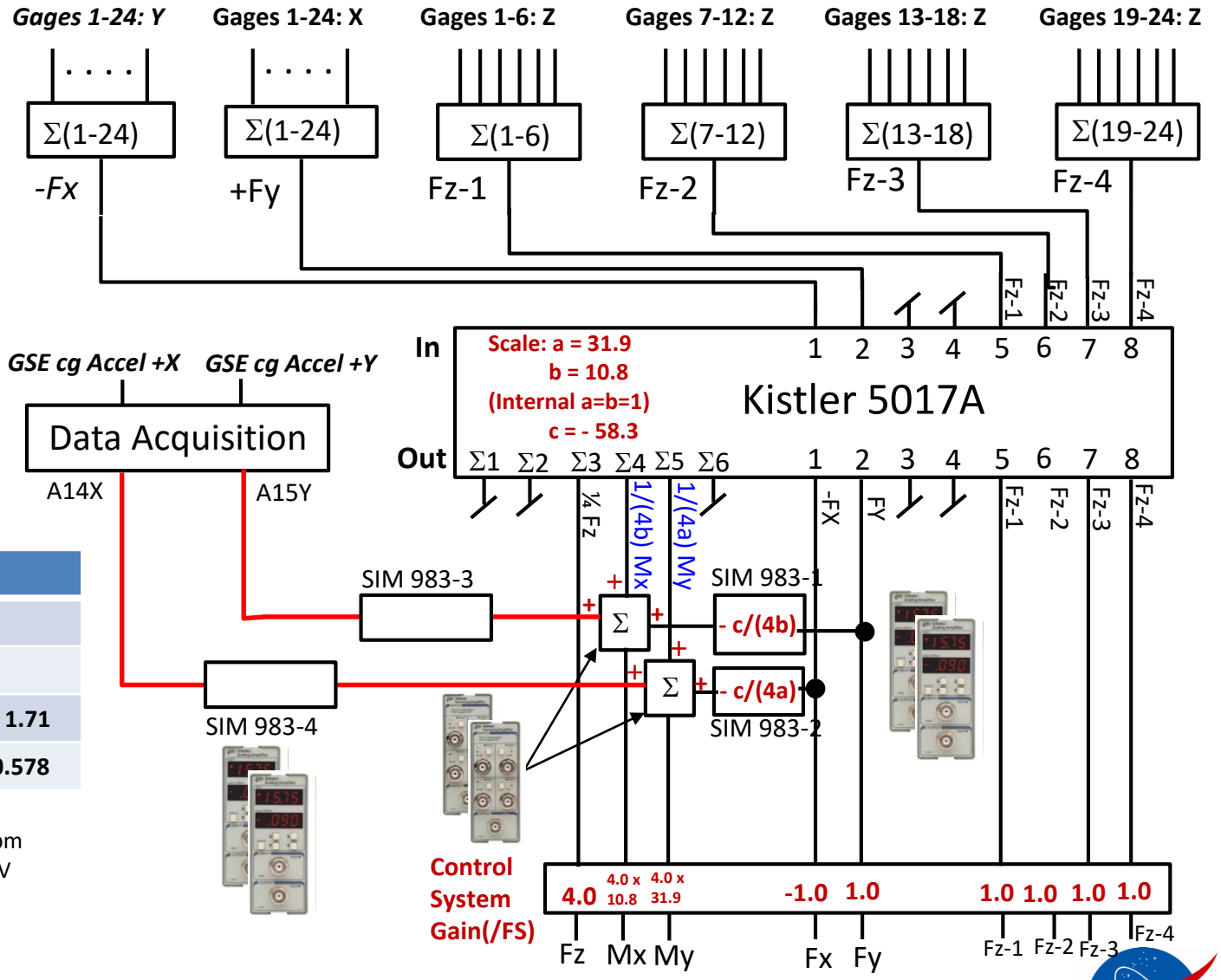


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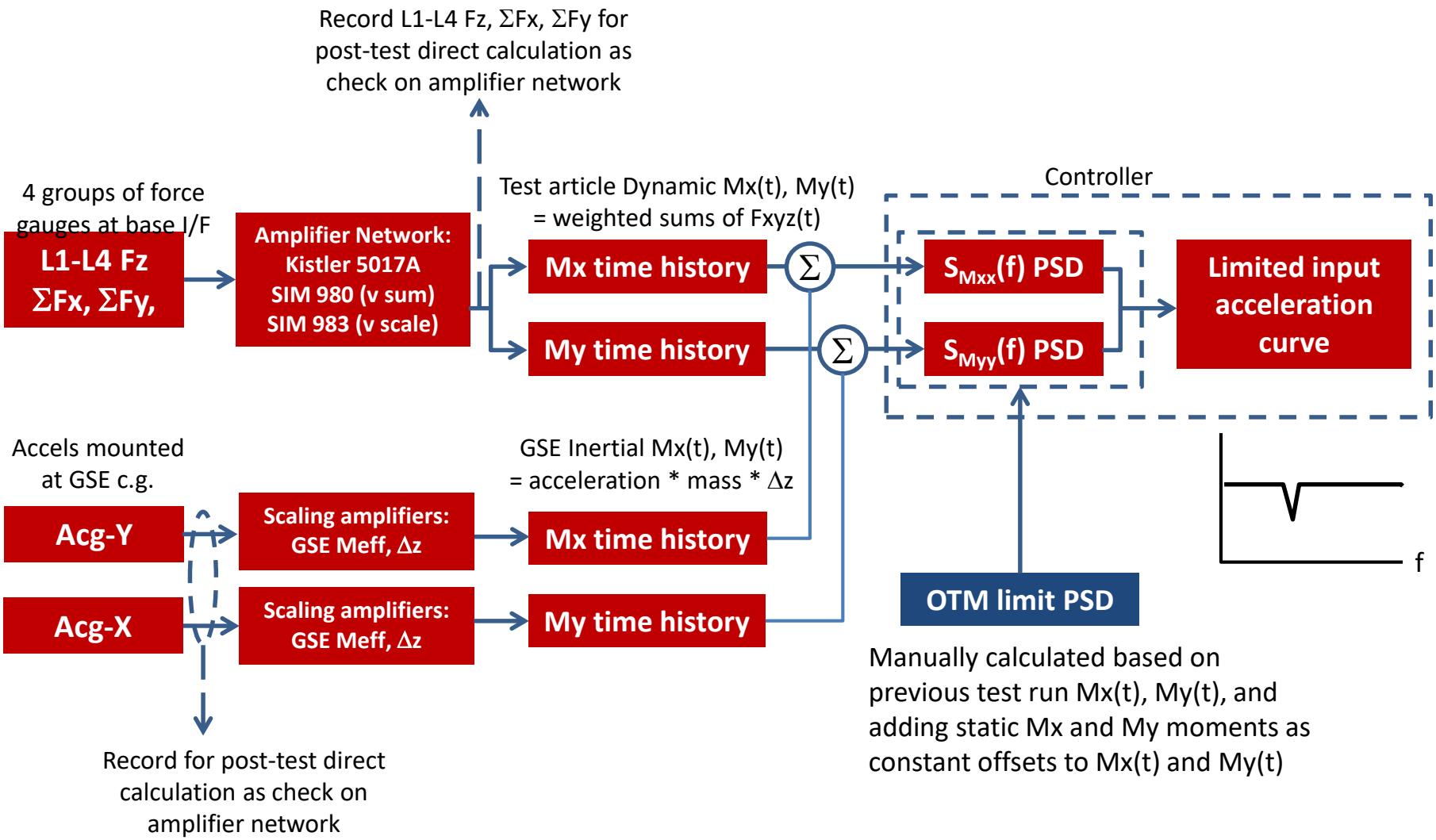
Diagram of Peak Moment Limiting Implementation

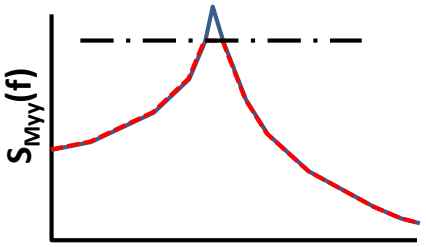


Determining Overturning Moment Spectral Limit

- Instantaneous resultant moment cannot be obtained in real time with current equipment (no multiplication function for squaring time histories)
- Challenge: Find a spectral $S_{Mxx}(f)$ and $S_{Myy}(f)$ limit that will result in limiting the instantaneous resultant $M_{xy}(t)$ peak value
- Requires statistical prediction of resultant time history peak from spectral RSS
- Use measured data from low level runs to calibrate prediction
  - Calculate statistical relationship between $S_{Mxx}(f)$ and $S_{Myy}(f)$ spectral averages and $M_{xy}(t)$ time history peak
  - Scale this relationship to predict future runs

Determining Overturning Moment Spectral Limit (cont.)

- Obtain measurements from lower level test run
- Use data for numerical simulation with trial limit profile for $S_{Mxx}(f)$ and $S_{Myy}(f)$



$\sigma_{My\_unlimited}$, $\sigma_{My\_limited}$ *

- Calculate predicted $Peak'_{Mxy}$ with trial limit profile

$$Peak'_{Mxy} = \sqrt{Mx_0^{\,2} + My_0^{\,2}} + k\sigma_{Mxy}\left(\frac{\sigma_{My\_Limited}}{\sigma_{My\_Unlimited}}\right)(scale)$$

σ_{Mx} or σ_{My} – whichever is dominant

Scale for next level run

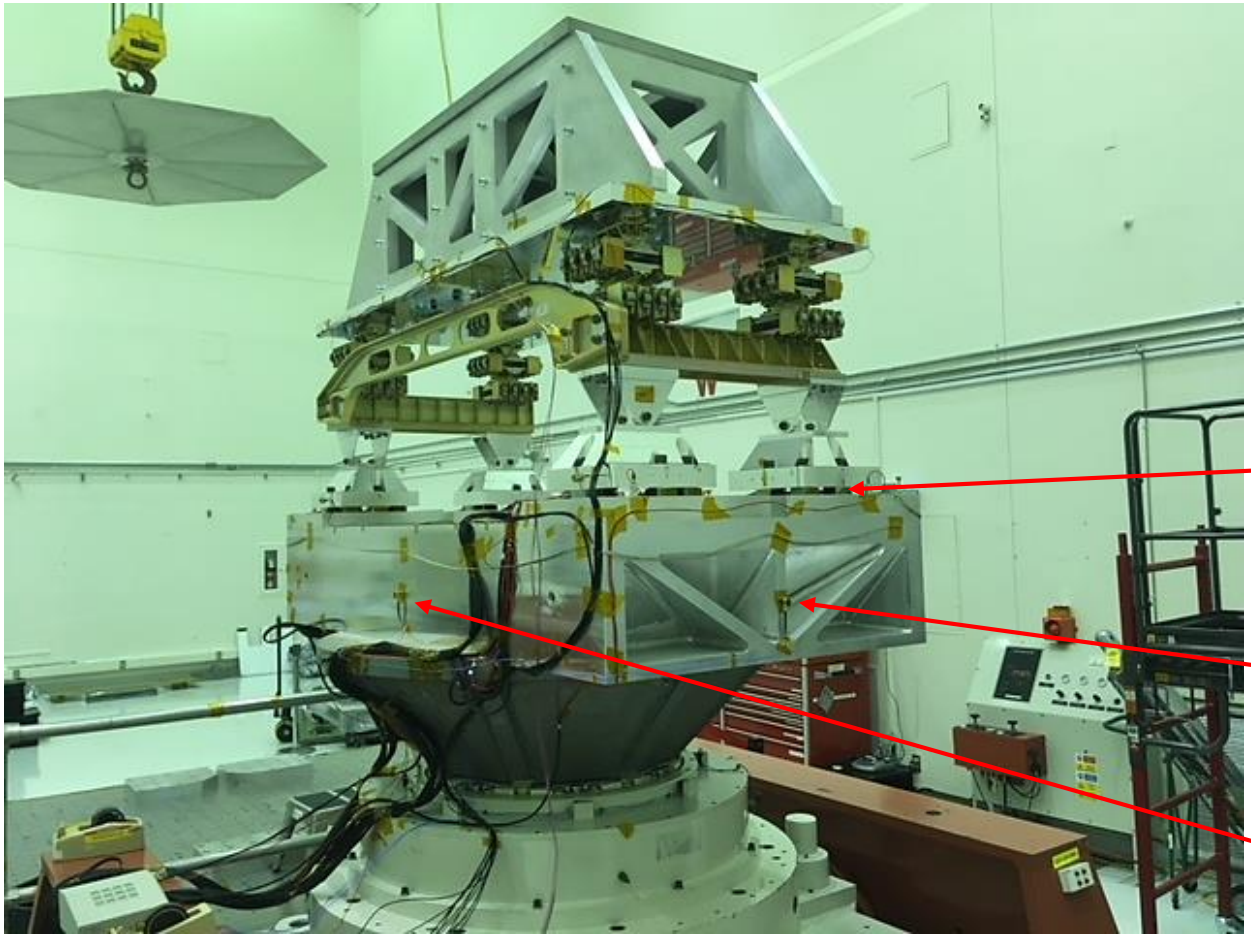
  - Peak factor k based on statistics and previous runs
  - Assumes σ_{Mxy} scales proportionally as the dominant σ_{Mx} or σ_{My}

- Re-iterate to find limit profile that results in desired peak limit
- Apply selected PSD limit profile for $S_{Mxx}(f)$ and $S_{Myy}(f)$ for next test run
- Adjust as necessary based on subsequent intermediate runs

Test

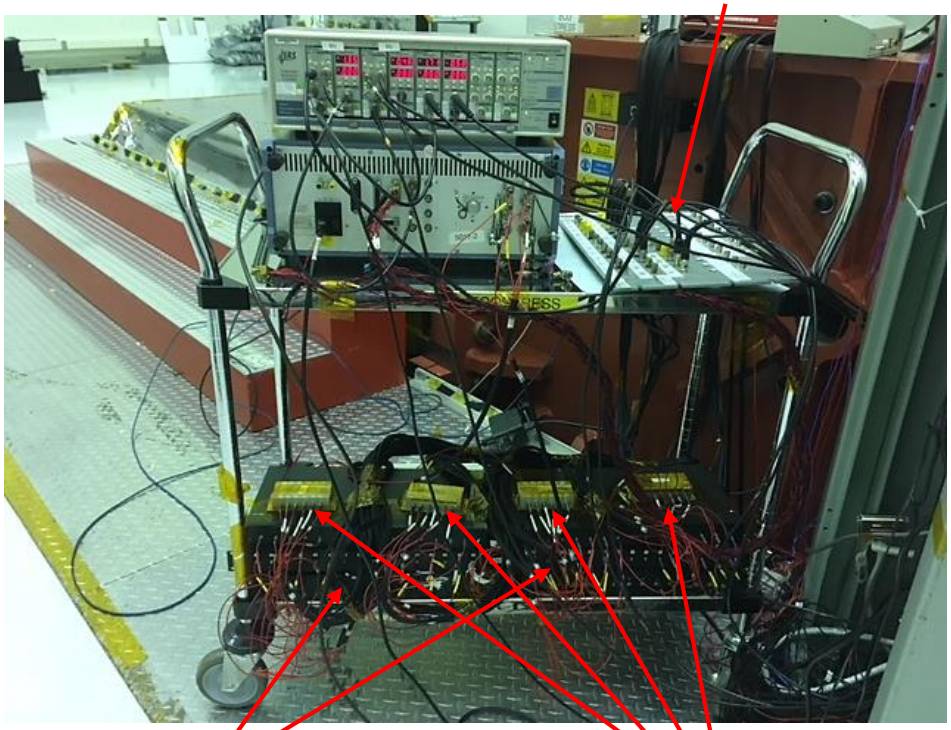
OCO-3 Mass Simulator on LVIS Isolation System

Z-Axis Test Configuration (OCO-3 Mass Sim on LVIS)



Moment Limiting Amplifier Setup

Patch panel for Kistler 5017A inputs/outputs

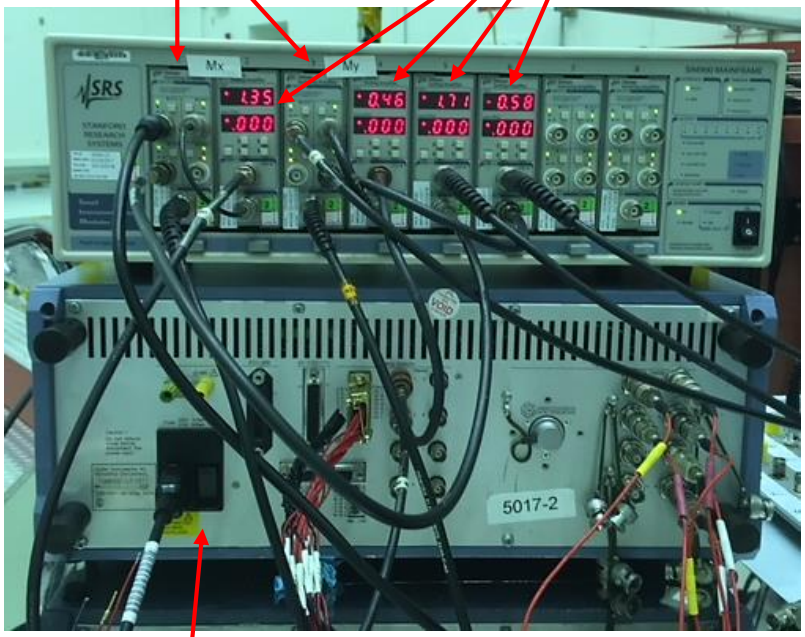


2 x 16-channel charge summing boxes

4 x 6-channel charge summing boxes

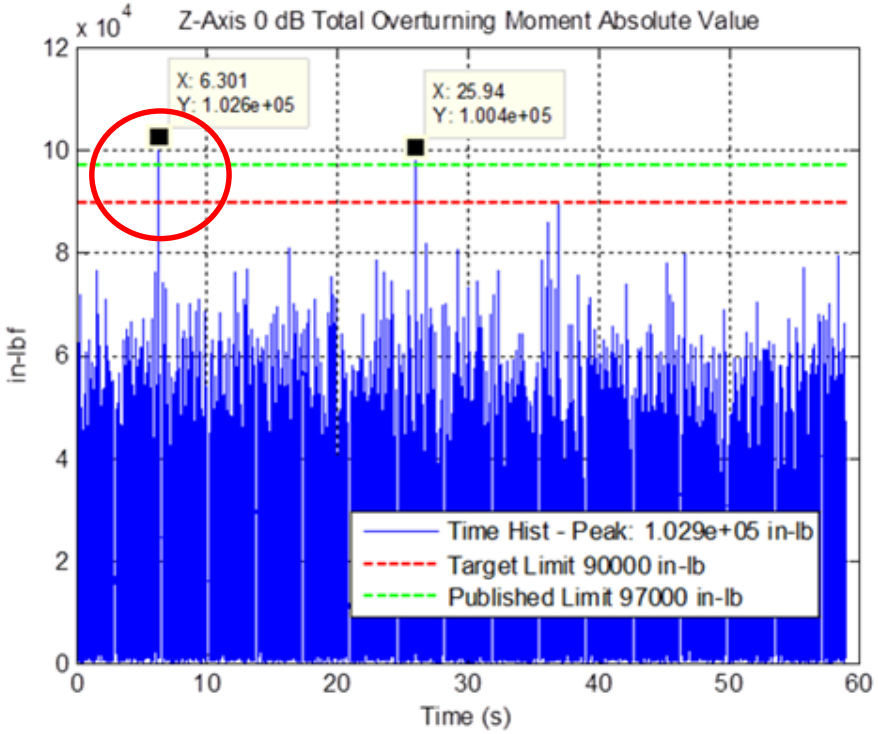
SIM 980 voltage summing amplifiers

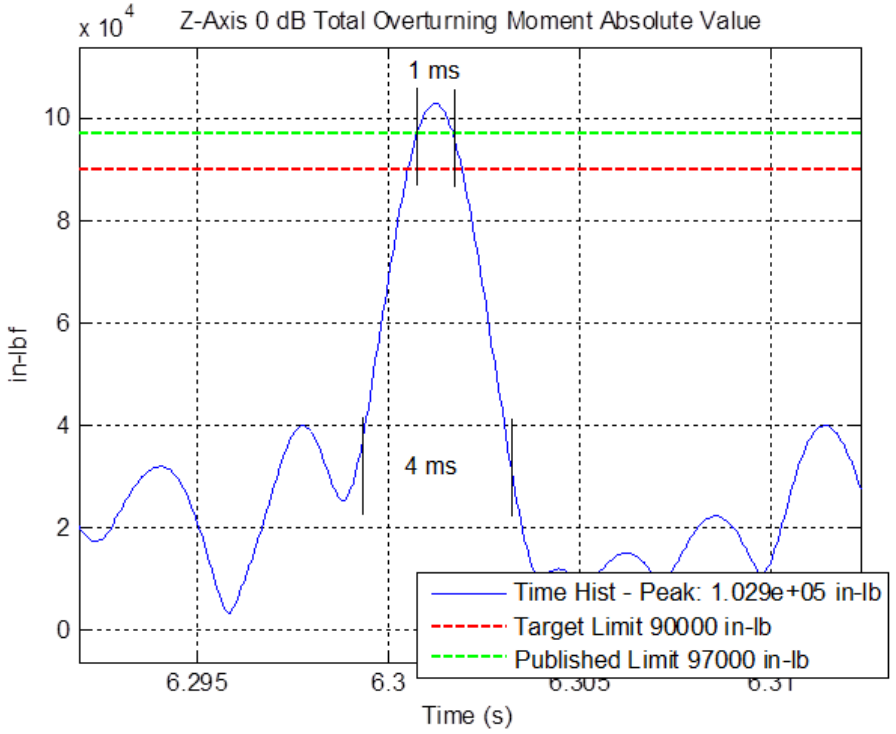
SIM 983 voltage scaling amplifiers



Kistler 5017A Multi-function amplifier

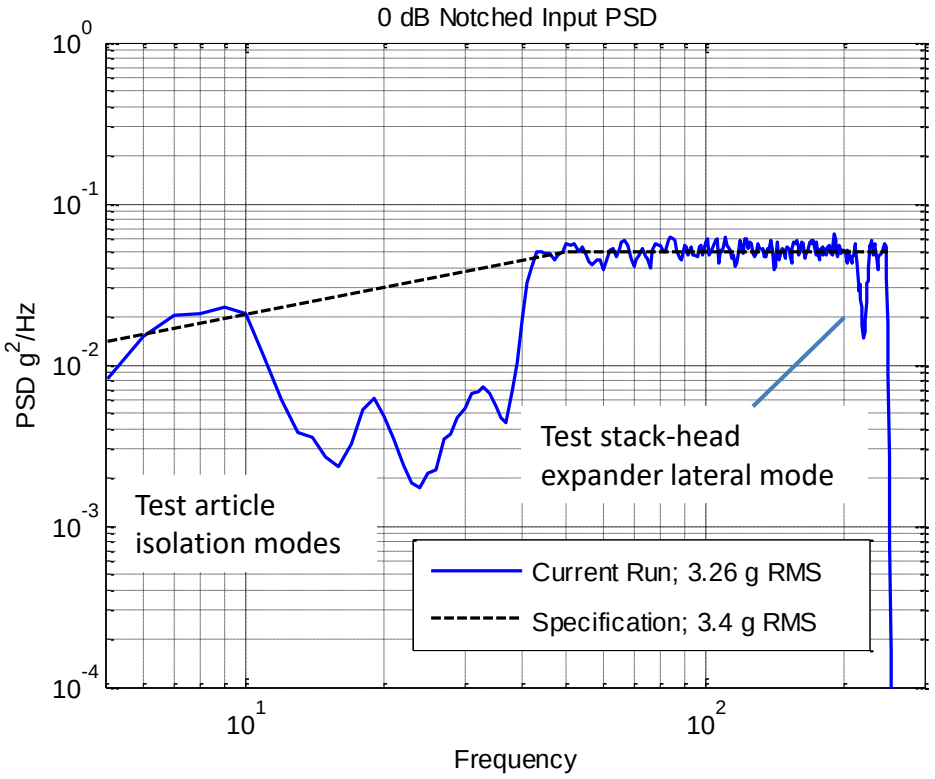
Moment Peaks Observed in 0 dB Run

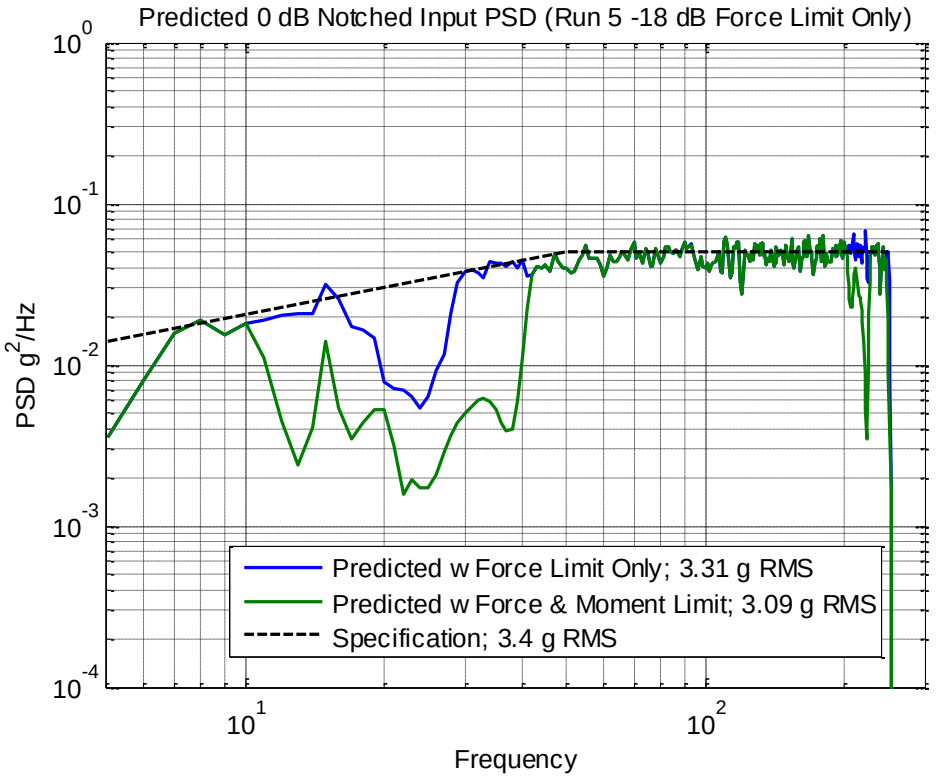




- Two peaks exceeded shaker 97,000 in-lb. rated limit
  - Consulted w shaker manufacturer; occasional exceedances not a concern, but aim to avoid
- All other peaks were below 90,000 in-lb

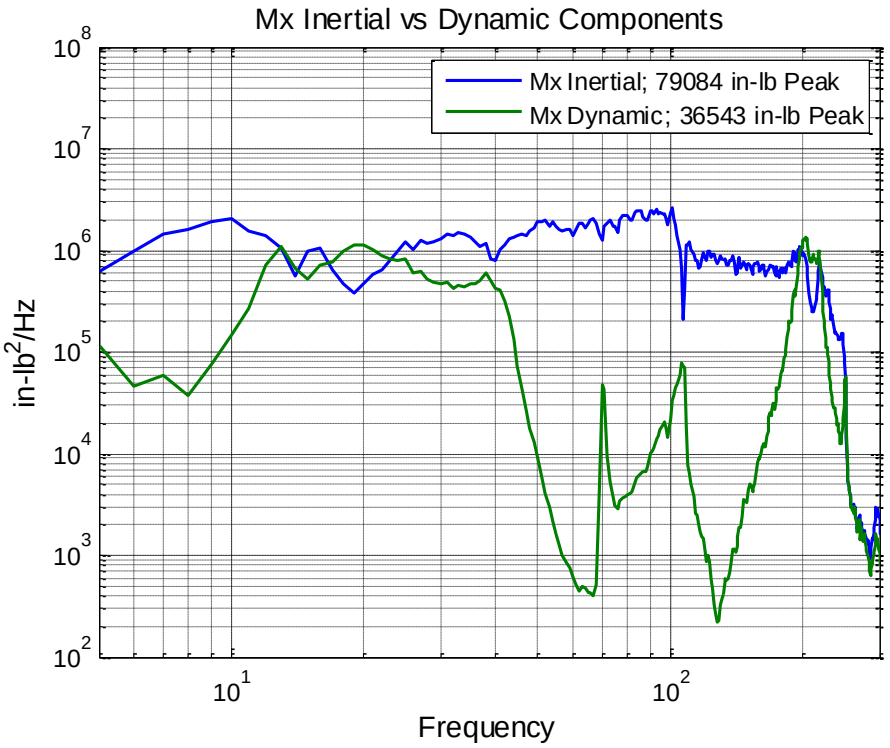
Resulting Input Notching from Moment Limiting

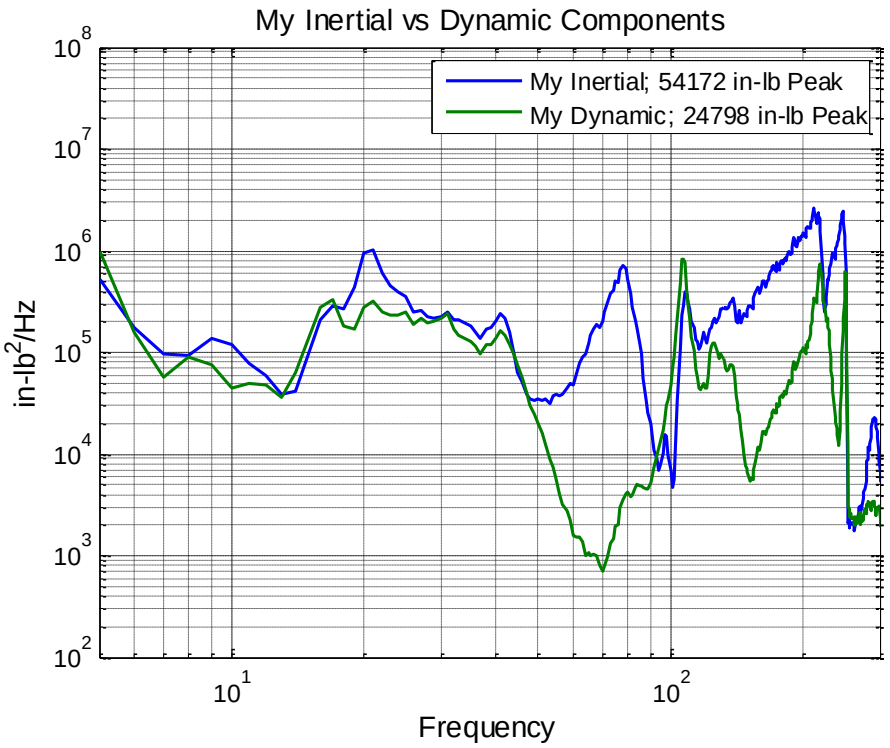




- Notching appears to reflect dynamic excitation of test article isolation frequencies
- Moment limiting dominates over force limiting

Relative Contributions of Test Article Dynamic and Fixture Inertial Overturning Moments





- Fixture/head expander inertial overturning moment is dominant contributor
- Large mass of GSE increases sensitivity of moment measurement to GSE cross-axis acceleration
- Dominance of GSE inertial moment in driving peak moment drove the limiting to result in significant notching

Lessons Learned

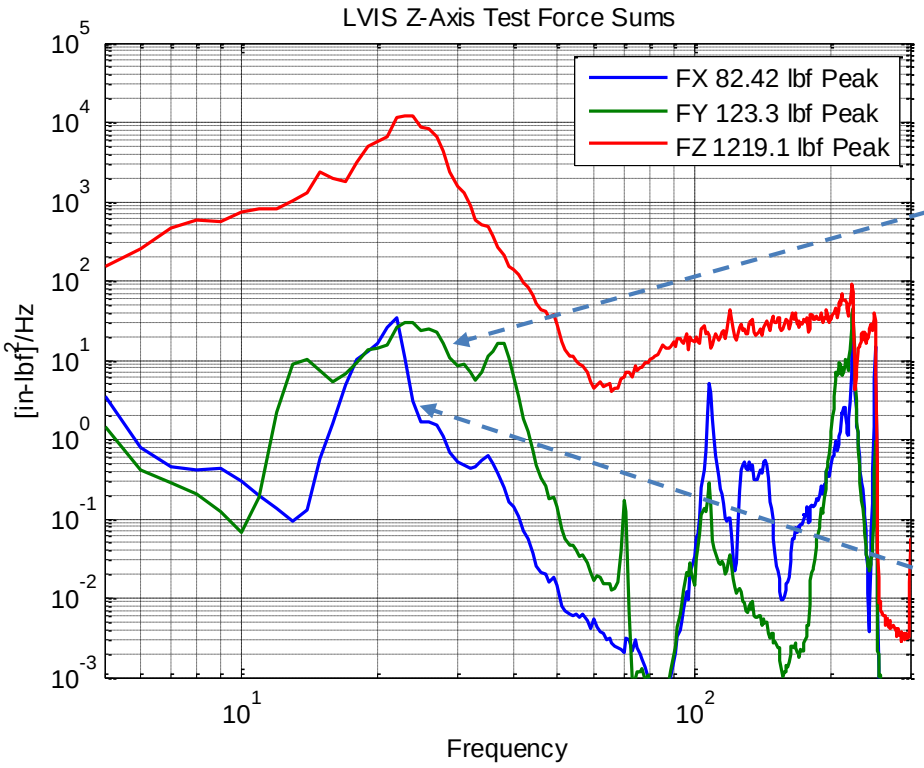
- Consideration of GSE inertial contribution to overturning moment control is critical as this may be a dominant component, particularly important when GSE is massive
  - OTM measurements/limiting may be dominated by small cross-axis GSE accelerations
  - Better to use larger head expander with edge guides for large tests and avoid necessity of massive fixture and provide more moment capability
- Pre-test modeling for large test articles should include flexible model of head expander
  - Needed to predict inertial OTM contribution

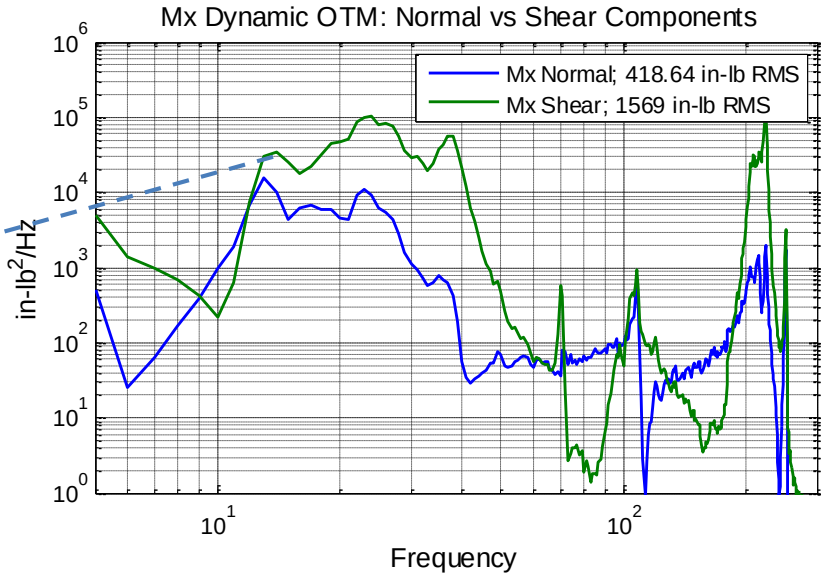
Other Lessons Learned

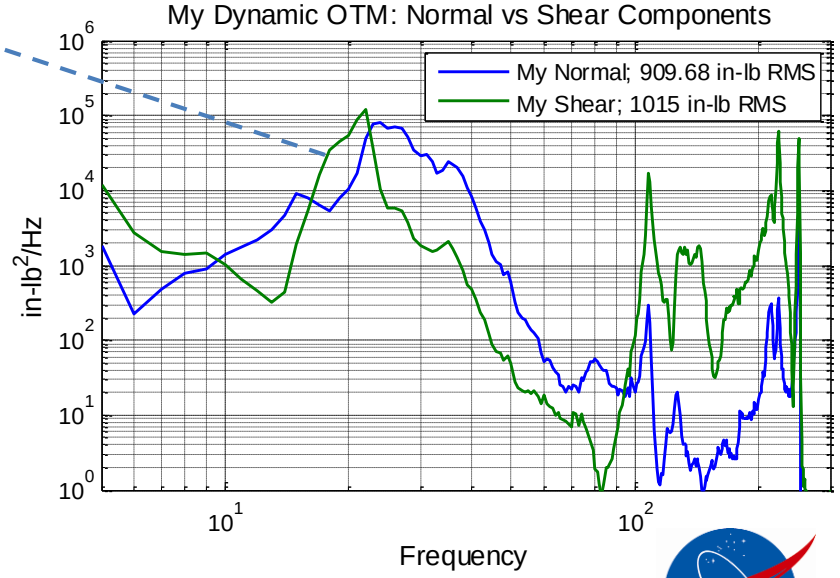
- 2 ms delay introduced in GSE inertial contribution to moment due to accelerometer signals feeding twice through DAQ system
  - Resulted in some inaccuracy in real-time moment signal
  - Correction: feed all signals together through DAQ system so they are time synchronized
- High frequency ringing of Al fixture contaminates c.g. acceleration time history measurements
  - Doesn't effect controller limiting, as ringing frequency well above input frequency range
  - Effects post-test time history peak predictions
  - Correction
    - Apply low pass filter to outputs before calculating time peak
    - Apply passive material between accel and fixture to dampen high frequency

BACKUP

Unlimited -18 dB Run - Test Article Dynamic OTM

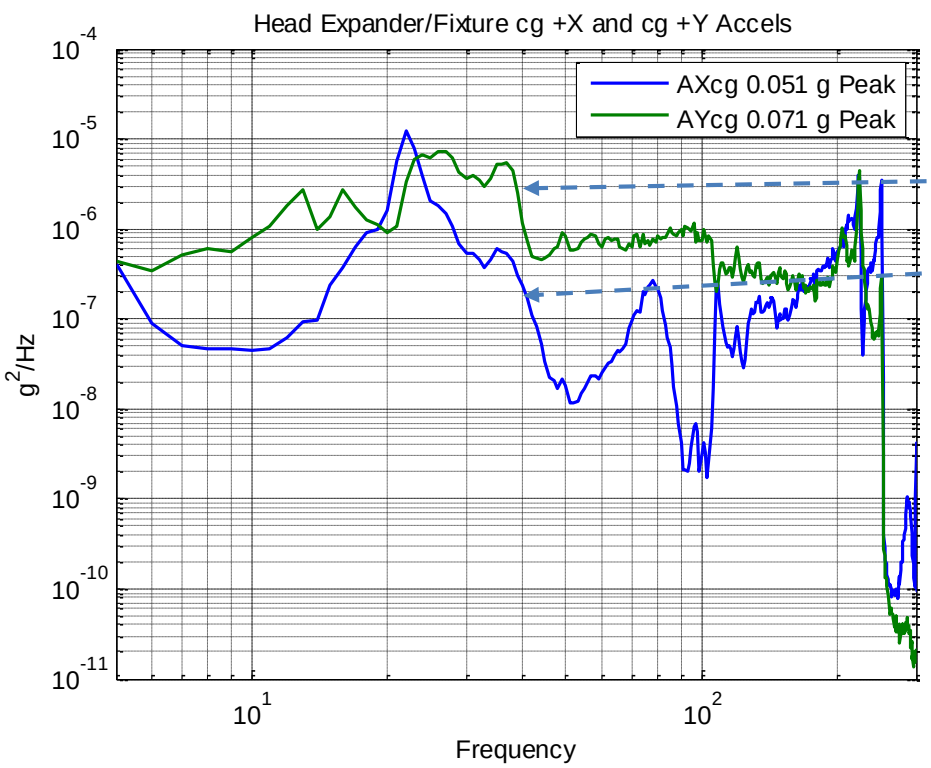


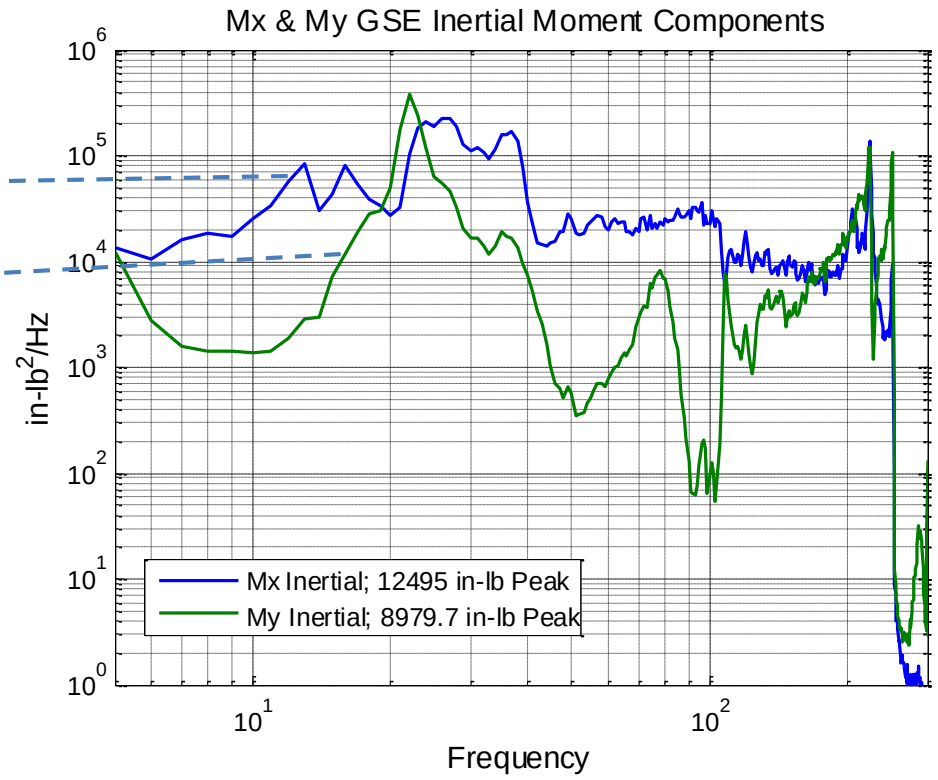




- Mx and My shear components are significant and driven by shear reacted forces

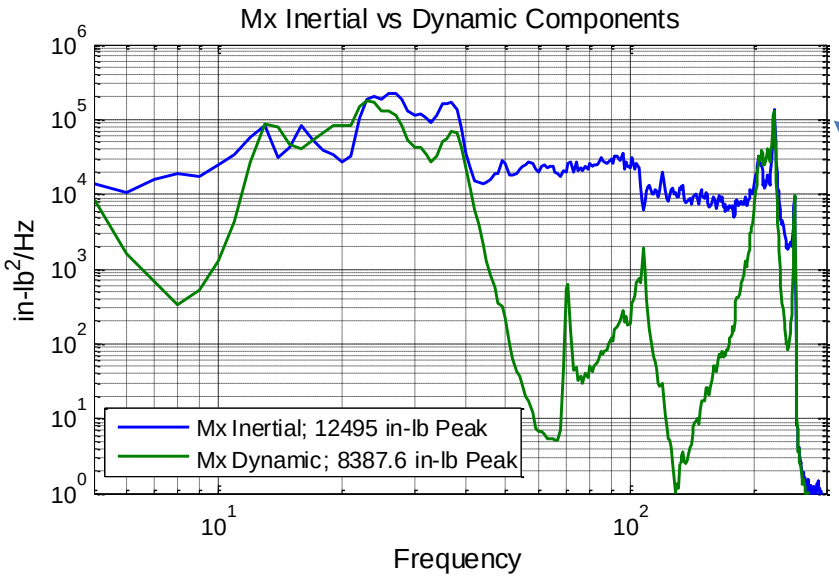
Unlimited -18 dB Run – GSE Inertial OTM

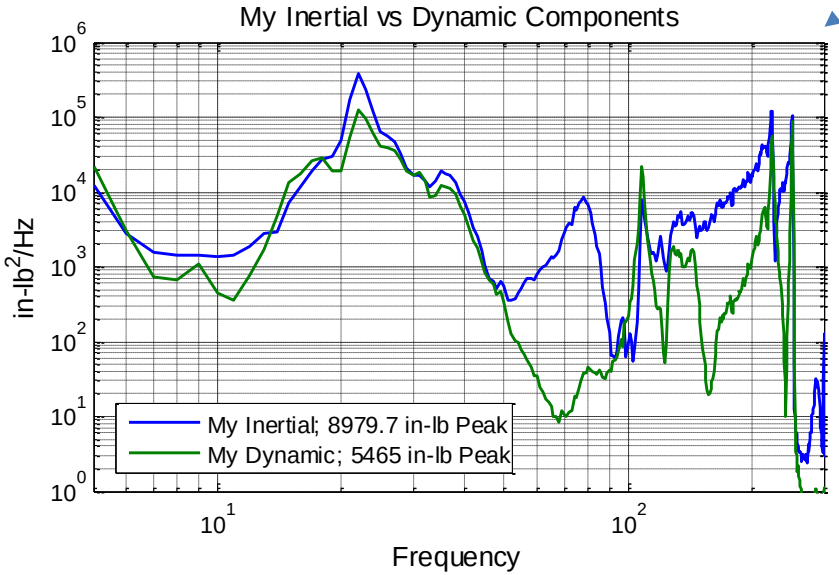


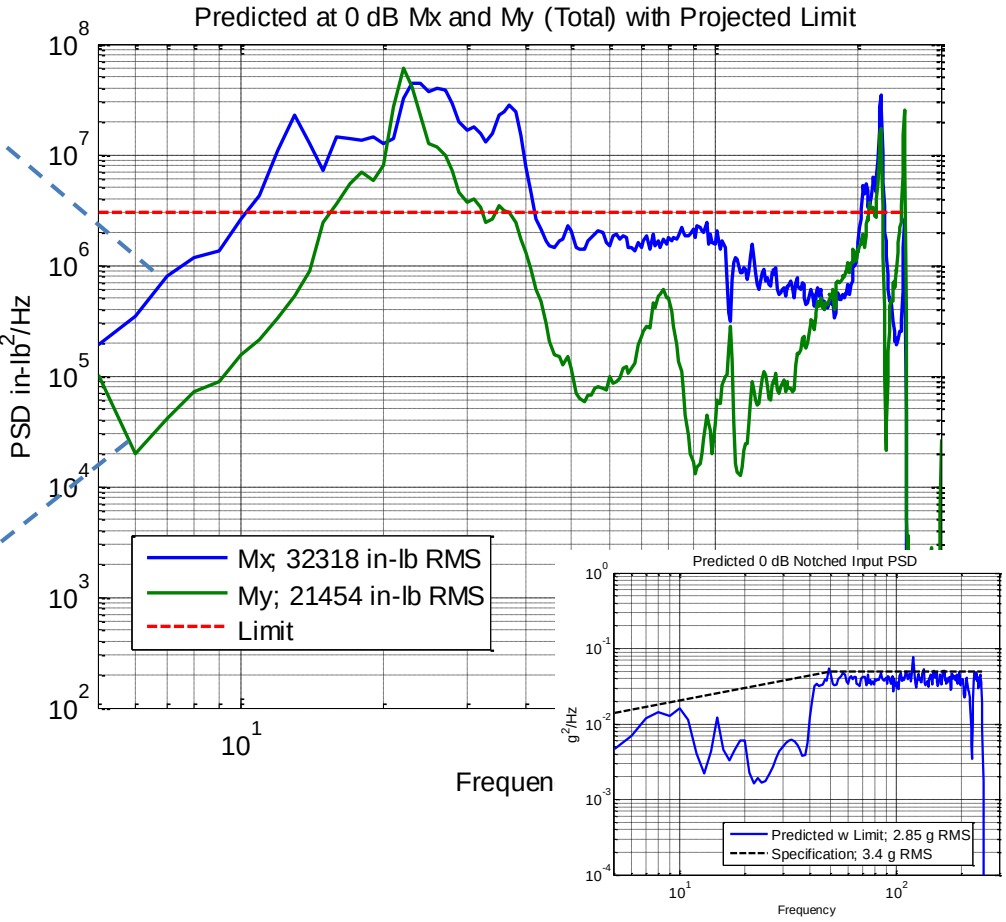


- With large GSE mass and Δz moment arm, very low acceleration levels can generate significant overturning moment
- GSE mass acceleration appears correlated with test article shear reaction forces

Unlimited -18 dB Run – GSE/HE Inertial OTM







- GSE inertial contribution is dominant and drives the limit at 0 dB